TORUS: Theory of Reactions for Unstable ISotopes

I. J. Thompson

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TORUS:

Theory of Reactions for Unstable iSotopes

A Topical Collaboration for Nuclear Theory
Project Period: June 1, 2010 – May 31, 2015

Midterm Progress Report
June 1, 2010 – July 31, 2012

Prepared by the TORUS Collaboration:

Goran Arbanas, Oak Ridge National Laboratory

Charlotte Elster, Ohio University

Jutta Escher, Lawrence Livermore National Laboratory

Akram Mukhamedzhanov, Texas A&M University

Filomena Nunes, Michigan State University

Ian Thompson, Lawrence Livermore National Laboratory (Coordinating P.I.)

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1 Introduction

Background

The TORUS collaboration is named from the research it focuses on, namely the **T**heory **o**f **R**eactions for **U**nstable i**S**otopes. It is a Topical Collaboration in Nuclear Theory, and funded by the Nuclear Theory Division of the Office of Nuclear Physics in the Office of Science of the Department of Energy. The funding supports a postdoctoral FTE for the years 1 through 4. The collaboration brings together a large fraction of the nuclear reaction theorists currently active within the USA.

Mission

The mission of the TORUS Topical Collaboration is to develop new methods that will advance nuclear reaction theory for unstable isotopes by using three-body techniques to improve direct-reaction calculations, and to integrate descriptions of direct and compound-nucleus reactions. This multi-institution collaborative effort is directly relevant to three areas of interest: the properties of nuclei far from stability; microscopic studies of nuclear input parameters for astrophysics, and microscopic nuclear reaction theory.

Highlights

1. Discovery and publication of a new method for describing transfers to resonances [21] – Section 3.4. A surface approximation, using neutron states defined by R-matrix parameters, is introduced – Section 3.1.

2. Testing and establishment of 'finite-range adiabatic distorted wave method' for deuteron stripping [28] – Section 3.2, and application to a wide range of (d,p), (p,d) and (p,α) transfer reaction experiments.

3. Detailed comparison of CDCC and Faddeev three-body calculations published by postdoc N. Upadhyay [36] – Section 3.2.

4. New formulation [23] of the Faddeev equations to include Coulomb distortion and target excitation – Section 3.3.

5. Development of coupled-channels theory for semi-direct capture mechanisms via giant-resonance and isobaric analog intermediate states — Sections 3.5 and 3.6.

6. 15 papers published and another 5 submitted – Section 7.2.

7. 38 presentations, including invited talks at various national and international venues, such as several ECT* workshops in Trento (4 talks), INT workshops in Seattle (3 talks), RIKEN meetings in Japan (2 talks), HITES conference (3 talks) and a plenary talk at CGS14 in Guelph, Canada.

8. Appointment of postdoctoral researchers Dr N. Upadhyay at MSU, Dr V. Eremenko at TAMU and graduate student L. Hlophe at OU — Section 5.

2 Overview

This report details our progress on the achievement of these milestones within the first 25 months of Years 1, 2 and the start of Year 3, and of our plans for the remaining half of the project.

Progress in reaction theory is characterized by the development of increasingly comprehensive descriptions of the underlying physical processes. This procedure is not perturbative in the usual sense, so it is crucial to carry out careful comparisons between different theories in order to identify the best approach for extending existing descriptions and developing new theories. A central part of our mission is the integration of three-body techniques into the treatment of direct reactions. To this end, we have completed careful comparisons of the well-established Continuum Discretized Coupled Channels (CDCC) method with exact three-body calculations within the Faddeev momentum space integral formalism (Section 3.2 and Publication [36]). We identified specific shortcomings of the CDCC method and developed a new formalism that makes it possible to implement a Faddeev treatment for (d,p) reactions on a wide range of targets (Section 3.3 and Submitted Publication [23]). We consider the insights gained from these comparisons and the subsequent development of the new formalism a major milestone of our project.

A primary motivation for our work originates from the new opportunities that rare isotope facilities offer now and in the future. It is therefore essential to clearly identify what can and cannot be measured in current and upcoming experiments. In this context we have investigated whether, and under which circumstances, transfer reactions probe the nuclear interior or the surface (Section 3.1 and Publication [20]). We have carried out studies for bound as well as resonance final states, as both types are important for extracting information that can be used to constrain nuclear structure models. In an extension of this work, we have developed a new formalism that makes use of concepts known from the successful and popular R-matrix theory (Section 3.4 and Publication [21]). The new formalism paves the way for an alternative description of transfers to resonances, able to characterize the measured cross sections in terms of resonance energies and widths, and thus to connect to astrophysically relevant capture reactions and nuclear structure studies. We consider the development of this new formalism, and the associated insights, a major development that both meets and surpasses the original objectives of our project.

A comprehensive description of binary reactions includes not only direct reaction processes, but also semi-direct and compound effects. For a proper description of neutron capture reactions, it is important to understand under which circumstances semi-direct capture via giant-dipole and isobaric analogue resonances contribute, and when compound-nucleus capture begins to dominate. This becomes particularly important for capture on nuclei outside the valley of stability, where level density effects are expected to play a crucial role. We have adapted formalisms describing semi-direct capture for use in our coupled-channels code Fresco and investigate the relative importance of direct, semi-direct, and compound capture, for selected isotopes of interest to astrophysics (Sections 3.5 and 3.6 and Submitted Publication [17]). We consider these developments crucial for a proper understanding of nucleon capture reactions. When completed for a wider range of isotopes, this will form a major milestone of our project.

Successful reaction theories require not only sound descriptions of the underlying reaction processes, but also proper physical inputs, in particular optical model potentials. We have investigated our options for implementing advanced optical potentials that were developed in the context of

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other projects and collaborations (Section 3.8 and Publication [26]). In addition to working with dispersive and microscopic folding potentials, we have also initiated an effort to develop separabilization methods in momentum space. The latter will be a crucial component for implementing the Faddeev approach described above. This development, as well as additional technical developments, such as the treatment of continuum states in two-nucleon transfer reactions, are important ingredients in support of our major milestones.

An integral aspect of our work is the training of the next generation of reaction theorists. During the first half of the project, we have hired and trained a young theorist, who has become the lead author of the comparison of the CDCC and Faddeev approaches. Due to some re-direction of funds, we were also able to seize the opportunity to involve a new postdoc (part-time) in the implementation of the Faddeev-based approach. We have also been able to involve and contribute to the training of one student: Linda Hlophe at Ohio. TORUS activities have also benefited Ngoc Nguyen and Luke Titus at MSU. Support from the DOE in the context of this project has not only be indispensable for implementing this training, it has also resulted in dramatically increased collaborative work between the institutions involved in the project.

Our objectives in the second half of the project focus on the implementation of the methods we have developed. This includes evaluating their accuracy and publishing comparisons with other methods, and demonstrating their applications in the analysis of present and planned experiments. Our ambition is to make codes available to the wider nuclear physics community and in particular experimental groups.

Specifically, we will implement the Surface Method for transfers to resonances specified by R-matrix parameters, for both DWBA and CDCC scattering. We will determine exterior prior and interior post contributions for such transfers and determine the accuracy of the Surface Approximation. This will enable experimentalists to measure resonance properties by transfer reactions. We will demonstrate the procedure with applications to published data.

A major effort will focus on the implementation of Coulomb-distorted AGS equations for d + $A \rightarrow$ p + B transfer reactions as a three-body problem, a project that requires significant computational work. We will also formulate low-rank separable expansions for optical potentials for inclusion in AGS equations.

As the results of three-body analyses of experiments become available, we will develop the necessary new semi-microscopic methods to treat doorway states in neutron scattering and capture. Specifically, we will formulate models for pygmy dipole resonances and isobar-analogue resonances, including multistep transfer contributions, to compute capture cross sections for selected neutron-rich nuclides. Related to this, we will determine the uncertainty of capture rates introduced by currently-used energy-averaging methods and investigate whether a new treatment is required that incorporates doorway resonances.

3 Research

3.1 Distinguishing Peripheral and Interior Contributions

Personnel involved: A.M. Mukhamdezhanov, F.M. Nunes, J.E. Escher, and I.J. Thompson

A crucial deliverable of any reaction theory is to determine what information can eventually be extracted from the analysis of the deuteron stripping data. It is well recognized by now that these reactions are mainly peripheral at energies $<$ 15 MeV/nucleon; the normalization of the external region is controlled by the asymptotic normalization constant (ANC). In 2011, A.M.M and F.M.N. contributed to the analysis of the astrophysically important reaction ^{14}C(d,p)^{15}C, which was measured, for deuteron energy $E_d = 17$ MeV, at the Nuclear Physics Institute, Prague-Rez, Czech Academy of Sciences, in collaboration with Texas A&M University and MSU/NSCL. As this reaction is a prime candidate for applying the generalized AGS equations developed by the TORUS collaboration, it deserves particular attention. The target is β-unstable with two neutrons outside the ^{12}C core and the loosely bound ^{14}C + n state is almost of single-particle nature. The direct radiative capture ^{14}C(n,γ)^{15}C plays an important role in nuclear astrophysics. The analysis of the reaction was carried out within the finite range adiabatic wave approximation [25], and a standard DWBA analysis was performed for comparison. A major conclusion of our study is that the ^{14}C(d, p)^{15}C reaction can be used as a tool to determine the ANCs, which in turn provides important information for calculating the (n, γ) cross section, but to obtain reliability and better accuracy it is necessary to go beyond DWBA. The findings are summarized in the paper [20].

In order to identify which part of the nucleus are probed by transfer reactions, A.M.M., I.J.T., and J.E.E. have examined the relative interior and exterior contributions of the reaction amplitude to calculated transfer cross sections. We considered stripping to both bound and resonance states. The reaction code FRESCO was modified in order to allow us to investigate separately the contributions from the internal and external parts of the reaction amplitude, where internal and external is defined in terms of the distance r_{nA} between the transferred neutron and the target. DWBA calculations were carried out for a range of targets, ^{12}C, ^{16}O, ^{20}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, and ^{208}Pb, for incident deuteron energies between 11 and 82 MeV. Some results are shown in Figure 1. Our main finding is that, although the post and prior DWBA amplitudes are equal, their behavior is quite different in the subspace over the variable r_{nA}. The prior formulation is clearly more sensitive to the nuclear interior (and thus to model assumptions about the interior structure), while contributions from the peripheral part of the $n+$ target system dominate the post form. Calculations for resonance states show similar trends, but with reduced contributions from the nuclear interior. We are working on optimization of the transition operator in the post form which will minimize the internal post contribution. This will make reaction amplitude of a pure R-matrix type, and improve the surface-domination of stripping to resonance processes.

The surface integral formalism, developed in an extension to this work (see Section 3.4), makes it possible to exploit this surface dominance. In this formalism, the transition amplitude is expressed as a sum of three terms: an interior prior term, an exterior post term, and a surface term: $T = T^{prior}(0, a) + T^{surf}(a) + T^{post}(a, \infty)$, with the notation $T(x, y)$ indicating the lower (x) and upper (y) limits of the integration, and the surface term being evaluated at the radius $r_{na} = a$. We find that for reasonable choices of a (around 7 fm), the surface term indeed dominates the
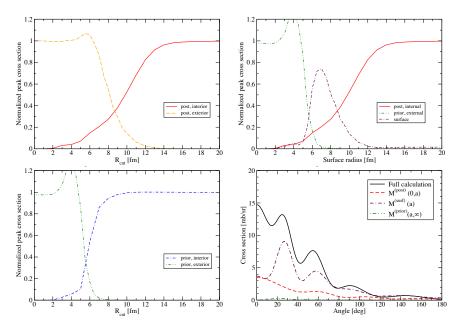
Figure 1: Examination of the role of interior, exterior, and surface contributions for $^{90}Zr(d,p)^{91}Zr$ stripping to the ground state. The two left panels give the contributions of the interior, $T(0,a)$, and exterior, $T(a,\infty)$, transition amplitudes to the cross section, in post (top) and prior (bottom) form. The upper right panel shows the contribution of the three terms in $T = T^{prior}(0,a) + T^{surf}(a) + T^{post}(a,\infty)$, as a function of the cutoff radius $R_{cut} = a$, which separates interior from exterior. In these three panels, peak cross sections are shown relative to the peak cross sections obtained in the full calculation. The fourth panel, bottom right, shows the contributions of the three terms to the angular cross sections, for $a = 7$ fm.

calculated transfer cross section, see Fig. 1. The analysis has so far been performed in the DWBA formalism, but will be extended to the coupled-channels approach. It can be shown that the exterior contribution does not have to be explicitly calculated in the CDCC approach, as it is contained in the breakup description. The implications of these findings are far-reaching and will be explored for stripping to resonances (see Section 3.4). In the context of this work, we also studied the convergence of stripping calculations for narrow and broad resonances. We are in the process of summarizing our findings for publication as a letter.

Plan: In an extension of this work, we will determine the size of exterior prior and interior post contributions for transfers to a wide range of resonances, to predict the accuracy of the Surface Approximation method of Section 3.4. We want to confirm in particular the smallness of the exterior prior contributions within the Continuum Discretized Coupled-Channels (CDCC) approach.

This work will be carried out by J.E. Escher, I.J. Thompson, A.M. Mukhamedzhanov, and V. Eremenko.

3.2 Breakup and Transfer Models

Personnel involved: N. Upadhyay (postdoc), F.M. Nunes, and Ch. Elster

One of the most well established theory for direct nuclear reactions is the Continuum Discretized Coupled Channels (CDCC) method. It includes breakup to all orders by discretizing the projectile continuum into bins. Alternatively, the 3-body problem can be solved exactly within

the Faddeev momentum space integral formalism (here denoted FAGS) which explicitly includes breakup and transfer channels to all orders.

With the aim of quantifying the accuracy of CDCC in computing elastic, breakup and transfer cross sections and establish a range of validity, we have completed a systematic comparison of CDCC and Faddeev. Our test cases consist of: i) d+^{10}Be at $E_d = 21.4, 40.9$ and 71 MeV; ii) d+^{12}C at $E_d = 12$ and 56 MeV; and iii) d+^{48}Ca at $E_d = 56$ MeV. These reactions were chosen to match available experimental data however the goal of the project was to understand the limitations of CDCC and therefore no fine tuning of interactions was performed. This work is published in Ref. [36]. As we summarize below, our results pose important constraints on the validity of CDCC when applied to deuteron induced reactions and call for a better description of the reaction dynamics.

Our CDCC/FAGS comparisons show no immediate correlation between elastic, transfer or breakup. In other words, finding agreement for the elastic for a given target and beam energy does not imply agreement in breakup or transfer. Indeed, these processes are sensitive to different parts of configuration space and therefore, only by looking at elastic, transfer and breakup simultaneously, can the CDCC method be thoroughly tested.

Overall, and regardless of the beam energy, CDCC is able to provide a good approximation to FAGS for *elastic* scattering. The inclusion of a neutron-nucleus bound state in the FAGS1 calculations introduces small modifications mostly are backward angles. Only for d+^{12}C at 12 MeV we found stronger discrepancies in the elastic angular distribution between CDCC and Faddeev-AGS.
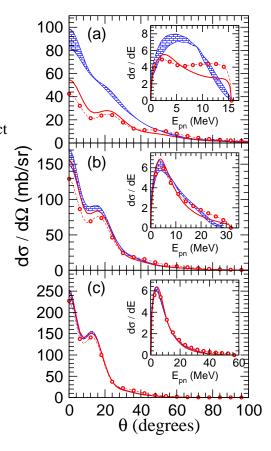

Figure 2: Breakup distributions for ^{10}Be (d, pn) ^{10}Be reaction at: (a) E_d = 21 MeV, (b) E_d = 40.9 MeV and (c) E_d = 71 MeV. Results for CDCC (hashed bar), FAGS(solid) and FAGS1 (circles).

The comparison of CDCC and Faddeev-AGS for *transfer* cross sections is consistent with the results presented in [28]. We found CDCC to be a very good approximation of FAGS1 at reactions around 10 MeV/u, but not so good for larger beam energies. What became clear from our study is that, for loosely bound s-wave dominated projectiles, CDCC does not improve the description of transfer when compared to the adiabatic model (ADWA). Because CDCC is computationally expensive, ADWA should be the preferred tool.

Breakup observables predicted by CDCC are at its best for the higher beam energies explored in this work. To reduce the technical challenges of the problem, we ignore the Coulomb interaction in the breakup comparison. Also, we use exactly the same Hamiltonian (CDCC and FAGS) to remove any ambiguity.

In Fig.2 we present the results for the angular distribution as a function of the c.m. angle of the pn system following the breakup on ^{10}Be at the three energies of choice. At the lowest energy,

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we find that CDCC does not reproduce FAGS, even taking into account the error estimated by model space truncation. At the higher energies, this discrepancy is removed. The insets of Fig.2 contain the corresponding energy distributions as functions of the proton-neutron relative energy E_{pn}. Again, a very large discrepancy is found at 21.4 MeV while fair agreement between CDCC and FAGS is obtained at the higher energies.

Similar conclusions can be drawn from the comparison of breakup angular and energy distributions for reactions on ^{12}C. Despite the large error bar in the CDCC predictions, there is a striking mismatch between CDCC and FAGS in both magnitude and shape of the breakup cross sections at 12 MeV. These discrepancies disappear at the higher energy. Agreement is obtained between CDCC and FAGS for the breakup of deuterons on ^{48}Ca at 56 MeV.

Although the calculations themselves represent a challenge, understanding the reason for the differences turns out to be even more challenging. We explored the effects of including the nA bound state in the transfer channel with FAGS1 (dotted circles). By comparing FAGS and FAGS1 we conclude that the effects of transfer are not negligible on breakup, particularly at low energies.

In addition we looked at the various components in the Faddeev approach. Strong contributions from the proton and neutron Faddeev components, not explicitly included in the CDCC expansion, are present when the proton-neutron relative energies are large. At low energy, the energy distribution is broad, the breakup to scattering states with large proton-neutron relative energy is important and therefore CDCC does not perform well. One possible solution to this shortcoming may be to use the CDCC wavefunction in a T-matrix that probes only short distances between the proton and neutron, instead of its asymptotic form. This work was published in Phys. Rev. C [36].

3.3   Generalized Faddeev Methods

Personnel involved: A. M. Mukhamedzhanov, V. Eremenko, Ch. Elster, L. Hlophe, F. M. Nunes, N. Upadhyay.

Deuteron stripping reactions have been a common tool to get spectroscopic information about single-particle levels, in particular, the spectroscopic factors, where the analysis of the data is based on the distorted wave Born approximation (DWBA). Among the higher order effects is deuteron breakup, which can be taken into account using the continuum discretized coupled channel (CDCC) method, the adiabatic wave approximation which is much simpler than the CDCC method, coupled reaction channel (CRC) approach, and the coupled channel Born approximation (CCBA). The advantage of the code FRESCO, written by I. Thompson, is that all these approaches are incorporated into the code. However, all these are still not able to reproduce the full complexity of the stripping reaction and it is the main goal of this project to deliver a new approach allowing one to calculate the deuteron stripping reactions on light and heavy isotopes over wide energy intervals. Our approach is incorporating the coupled reaction channels to all significant orders necessary to achieve required accuracy. The only method, which is able to incorporate all the coupled channels in deuteron stripping without double counting of nonorthogonal channels is the Faddeev approach. In recent very important works done by F. M. Nunes and N. Upadhyay (Section 3.2) for the first time Faddeev calculations were systematically compared with the CDCC ones for the deuteron stripping on light nuclei. The found deficiency of the CDCC method underscored once again the necessity of the delivering of full scale Faddeev code available for analysis

of the deuteron stripping with possible extension for analysis of other transfer reactions induced by light projectiles. Currently the only code of the Faddeev equations in the Alt-Grassberger-Sandhas (AGS) form developed by A. Deltuva uses the Coulomb potential screening and can be applied only for analysis of the deuteron stripping reactions on light target (charges $Z \lesssim 20$). Another setback in the existing AGS code by Deltuva is that target excitation is not included, but this may play an important role in the deuteron stripping.

Our final goal is to use the deuteron stripping reactions as indirect tool to get the information about (n,γ) processes on exotic nuclei important for nuclear astrophysics and applied physics. It requires to have a method which allows one to analyze deuteron stripping on targets with $A \sim 100$ or higher. To do it within the Faddeev formalism one has to abandon the Coulomb screening method and take into account the Coulomb interaction explicitly.

AGS form equations with target excitation and Coulomb interactions

Personnel involved: A.M. Mukhamedzhanov, V. Eremenko

The original Faddeev equations are written for $3 \rightarrow 3$ collisions. To apply them for the deuteron stripping it is convenient to rewrite them in the AGS form, in which the Faddeev equations are written directly for coupled reaction amplitudes for $2 \rightarrow 2$ binary processes. These AGS equations are used as a starting point. However, these equations are not enough to take into account the whole complexity of the deuteron stripping reactions, because in the Faddeev approach the target is treated as a structureless constituent particle.

During the first half of 2012 (second year of our Collaboration) A.M. Mukhamedzhanov developed a new formulation of the generalized Faddeev equations in the AGS form for the deuteron stripping, which includes explicitly the Coulomb interactions and target excitations. It is important to underscore that the Faddeev equations in the AGS form with explicit inclusion of the Coulomb interaction have been derived for the first time. The Coulomb interaction in the AGS approach appears in the three-ray vertex form factors in the effective potentials and in the four-ray vertex in the triangular diagrams. Applying the two-potential equation allows one to remove the non-compact singularity in the triangular diagram describing the elastic scattering and containing the p–A Coulomb scattering amplitude. The AGS equations can also be rewritten in the Coulomb distorted wave representation, in which the reaction amplitudes and the effective potentials are sandwiched by the Coulomb distorted waves in the initial and final states. Another important topic of our research is the investigation of the singularities of the integrals containing the off-shell Coulomb scattering amplitude. This is necessary to prove the compactness of the Faddeev equations. The practical application of the obtained equations requires regularization of the integrals containing the off-shell Coulomb scattering amplitudes. Note that in a standard procedure involving the screening of the Coulomb potential, it is tacitly assumed that, in the limit of the screening radius $R \rightarrow \infty$, all the integrals containing the Coulomb scattering amplitude have well-defined limits and that the Coulomb screening affects only the Coulomb distorted waves in the initial and final states.

In the case under consideration, when only two particles are charged, only one off-shell Coulomb scattering amplitude of the p–A scattering is needed. It is shown how to deal with all the integrals containing the Coulomb off-shell T-matrix. Applying our regularization procedure, we obtain the

expression for the effective potentials in the AGS equations which are free of the singularities caused by the Coulomb distortions in the initial and final states. It is shown that the Coulomb-modified form factors in the transfer amplitudes and in the triangular diagrams do not contain non-integrable singularities. The target excitation is taken into account following the formalism developed by projecting space on the three-body one. The final generalized AGS matrix equations are written in the form which includes explicitly Coulomb interactions, target excitations and spins of the particles. The work has been submitted for publication [23].

Because the solution of the AGS equations is greatly simplified for separable potentials, we use a separable potential approach, assuming that these approximate the realistic NN potentials and NA optical potentials. The important code to represent these potentials in a separable form is being developed by us at Ohio (see Section 3.8). These will later be generalized to include target excitation, and enable us to go beyond simple models of three inert bodies.

Plan: Postdoc V. Eremenko will write a new code to solve the generalized Faddeev equations. Postdoc N. Upadhyay from MSU/NSCL also will participate in this effort in Year 3.

3.4 Transfers to Resonances

Personnel involved: A.M. Mukhamdezhanov, J.E. Escher, I.J. Thompson, and G. Arbanas

One important activity of the TORUS collaboration is the development of a theoretical description of stripping to resonances that provides valuable insights into the structure of the resonant state. The necessity for theoretical advances in this field is due to the fact that the number of experiments leading to population of the resonance states is mounting, but there are no good descriptions and readily-available codes that can be used to analyze the data.

There are two main reasons for the lack of a practical theory of stripping to resonance states that could be used by experimental groups: the numerical problem of the convergence of the distorted-wave Born approximation (DWBA) matrix element when the full transition operator is included, and the ambiguity over what spectroscopic information can be extracted from the analysis of transfer reactions populating the resonance states. Since the resonant binary amplitudes in the very popular R-matrix approach are parameterized in terms of the observable partial resonance widths, it is quite natural and useful to pursue a theory in which the transfer cross sections are parameterized in terms of the same observables as in applications to binary resonance reactions.

In April 2011, A.M.M. initiated work on a new Surface Method for deuteron stripping reactions that populate resonance states. This method is based on the surface integral formulation of the reaction theory, outlined in [16], and a generalized R-matrix approach. The formalism was first developed for the DWBA and subsequently extended to the continuum discretized coupled channels (CDCC) approach, which is the ultimate goal of this work. The CDCC wave function takes into account not only the initial elastic d + A channel but also its coupling to the deuteron breakup channel p + n + A that is absent in the DWBA. Stripping to both bound states and resonances can be treated in this formalism.

The reaction amplitude is expressed in terms of the resonance partial widths, boundary conditions and channel radii, i.e. exactly the same quantities that appear in the analysis of binary resonance reactions in the R-matrix approach. This makes it, in principle, possible to simultane-

ously analyze deuteron stripping to resonance states and binary resonance reactions. An important step in the derivation of the reaction amplitude is the split of the configuration space of the sub-system "transferred nucleon-target" into the internal and external regions, similarly to what is being done in the R-matrix approach. In the post CDCC approach the reaction amplitude is given by the surface integral and the internal post form CDCC amplitude, which is expected to be small compared to the surface integral. The absence of the external amplitude in the CDCC approach solves the convergence problem. The expression for the amplitude has been derived for the general two-channel, multilevel-case and will allow one to analyze practically all possible cases, including sub-threshold resonances. The theory provides a consistent tool to analyze both binary resonant reactions and deuteron stripping in terms of the same parameters. Thus, for the first time, the theory of the deuteron stripping to resonance has been developed in a form that allows experimentalists to analyze experimental data and obtain resonance partial widths. Spectroscopic factors do not enter into the analysis. A summary of the work was published in [21].

The newly-developed theory for deuteron stripping to resonance states has been applied to the analysis of the Trojan Horse (TH) resonance reactions, in the plane-wave limit. The first application of the developed surface integral formalism in the plane wave approximation for the reaction ^{19}F(p,α)^{16}O has been presented in [6].

Plan: We will incorporate the formalism developed by A.M. Mukhamedzhanov into a modified Fresco code. This will be tested by various test applications, e.g. partial widths will be extracted that can be compared with known results from (n,α), (p,α) and (n,γ) reactions. The effects of deuteron breakup in the initial channel will be considered using the CDCC approach. We will also investigate the possibility to simultaneously fit resolved resonance parameters and the smoothly varying cross section, which would be a useful development for the nuclear data community.

This work will be carried out by A.M. Mukhamedzhanov, J.E. Escher, I.J. Thompson, and G. Arbanas, as well as the new postdoc V. Eremenko.

3.5   Capture Reactions

Personnel involved: G. Arbanas, I.J. Thompson, and J. Escher

3.5.1   Semi-direct capture mechanisms

It was recognized in the 1970's that semidirect capture, a two-step process that excites a giant-dipole resonance in the first step, followed by its radiative de-excitation in the second step, is a dominant process near giant-dipole resonances in the neutron energy range 5-20 MeV. For neutron energies below 1 MeV that are of astrophysical interest, contributions from semidirect processes are smaller than those of direct capture, but have nevertheless been computed to be as high as 50% on nickel. These considerations motivated us to implement semidirect capture in a coupled-channel code FRESCO.

Capture cross sections on and near doubly "magic" nuclei like ^{132}Sn are needed to improve accuracy of astrophysical nucleosynthesis models. This motivated our collaborator R. Kozub to measure of ^{130}Sn(d,p)^{131}Sn in inverse kinematics, from which single-particle energies and spectroscopic factors in ^{131}Sn were computed. These single-particle level parameters were then used to

compute direct + semi-direct (DSD) capture process ^{130}Sn(n,γ)^{131}Sn using FRESCO and an older DSD code CUPIDO. For neutron energies 5-20 MeV we find the semidirect capture via giant-dipole resonance to be dominant over direct capture, but for neutron energies below 1 MeV, of interest to astrophysical nucleosynthesis models, we find semidirect to be less than 5% of the direct capture. This work is submitted for publication [17].

Furthermore, we assessed relative contributions of DSD and compound capture cross section on ^{130}Sn(n,γ)^{131}Sn below 1 MeV by comparing our DSD computation to statistical capture cross section that we computed using a Hauser-Feshbach (HF) code TALYS. For this HF computation we used a parity-dependent level-density model, since parity-dependence in conjunction with selection rules is expected to affect the low-energy electric dipole (E1) capture of s-wave neutrons. A comparison of HF captures using parity-dependent vs. parity-independent level density models revealed an increase in capture of about 30% using a model of Loens *et al.* [19]. A parity-dependence in level density was found to be relatively small, in large part due to the $h_{11/2}$ single-particle level that opens up a large number of negative parity-states in ^{131}Sn even at low excitation energies. A more accurate treatment of parity dependence in HF calculations would involve individual treatment of neutron partial waves and their respective level-densities.

Plan: Apply the newly-implemented direct-semidirect capture formalism to additional nuclides of importance to nuclear astrophysics, such as isotopes in the iron-nickel region, and publish the results.

3.5.2 Energy-averaging in statistical reaction models

A systematic comparison of computed capture rates (i.e. Maxwellian averaged capture cross section at temperature of 30 keV) to capture rates based on existing data reveals disagreements, in some cases by factors on the order of two or greater, as reported by Bao *et al.* [1]. A possible source of this discrepancy is the fact that the computation of astrophysical neutron capture rates involves energy-averaging of Hauser-Feshbach (HF) capture cross sections using a Maxwellian energy distribution with a width of approximately 0.1 MeV. The HF capture cross section is a product of a compound formation transmission coefficient and a gamma-ray transmission coefficient. The former is computed for an optical model potential and is therefore implicitly energy-averaged over an interval characteristic to optical potentials, which is on the order of 1 MeV.

Plan: We will determine the uncertainty of capture rates introduced by currently-used energy-averaging methods and investigate whether a new treatment is required that incorporates doorway resonances.

3.6 Isobaric Analogue Resonances

Personnel involved: G. Arbanas and I.J. Thompson

The position and width of isobaric analogue resonances in nucleon-nucleus scattering are accurate and detailed indicators of the positions of resonances and bound states with good single-particle characters [3]. Since determining the positions of shells and shell gaps has often been the objective of experiments with unstable isotopes, measuring isobaric analogue resonances (IAR) should be modeled as well as possible by theorists in relation to proposed experiments. These IAR

have the great virtue that *neutron* bound states, both occupied and unoccupied, can be determined in experiments that react *protons* on nuclei. Proton targets can be made with hydrogen. The best information about levels is determined by $(p,p'\gamma)$ coincidence experiments [30]. The displacement energies of IAR also depend critically on neutron-proton density differences, so can be used to probe those densities in the surface.

We therefore implemented within our coupled-channels code FRESCO the main Lane coupling term [18]: the charge-exchange interaction that transforms an incident proton into a neutron. Because of Coulomb shifts, the neutron will be at a lower energy, such as a sub-threshold energy near an unoccupied single-particle state. We see doorway resonances when the neutron energy is near a bound state. At the same time, a target neutron must have changed to a proton, so it must have been in an occupied neutron state with quantum numbers such that a proton with those parameters is not Pauli blocked. We therefore extended the Lane coupled-channels formalism to follow the non-orthogonality of this neutron channel with that configuration of an inelastic outgoing proton, and the target being left in a particle-hole excited state. This is being tested for ^{208}Pb, for which good $(p,p'\gamma)$ coincidence data exists [30], and we will soon make predictions for the equivalent processes for ^{132}Sn, and talk to experimentalists about possible experiments. Experiments such as [32] show the methods are also useful for light nuclei.

Plan: We will complete testing of our treatment of isobar-analogue resonances, including multistep-transfer contributions, and compute cross sections for selected neutron-rich nuclides.

3.7 Pair Transfers

Personnel involved: I.J. Thompson

In Year 2, we have calculated two-nucleon transfers for the (p,t) and (p,^{3}He) reactions on a wide variety of nuclei using overlap form factors from the shell-model code OXBASH, in collaboration with B.A. Brown (MSU). A systematic front-end to FRESCO was written which enables the easy calculation of both simultaneous and sequential transfer reaction mechanisms.

Plan: In Year 3, we will calculate two-nucleon transfers for the (p,t) and (p,^{3}He) reactions using overlaps from the No-core-Shell-Model, and also the Variational-Monte-Carlo method when available.

3.8 Implementing Advanced Optical Potentials

3.8.1 Separablization of Optical Potentials in Momentum Space

Personnel involved: Ch. Elster and L. Hlophe (graduate student, Ohio University)

For the generalized AGS equations adapted to calculate (d,p) reactions for arbitrary nuclei, we proposed to use separabilized potentials between the constituents of the reaction. While there is a large body of work on separable representations of the nucleon-nucleon interaction (see e.g. [13, 2]), and some in the three-body description of light nuclei like ^{6}He [10] and ^{6}Li [9], we are not aware of similar work for heavy nuclei. The separable potentials for ^{6}He and ^{6}Li are essentially inspired by the Unitary Pole Approximation (UPA) around resonances, and contain Yamaguchi-

type form factors as they are common in the description of the NN interaction.

For describing (d,p) reactions within a Faddeev formulation one needs the interaction between the constituents in the system. For nuclear reactions this means the nucleon-nucleon interaction for the deuteron subsystem and the neutron or proton optical potentials between the neutron and proton in the deuteron and the target nucleus.

For developing a momentum space separable representation of nucleon-nucleus optical potentials and their transition matrix elements, the latter being the quantities entering the Faddeev description of the (d,p) reaction, we will need a separabilization formulation that is sufficiently general that it can be used for a variety of nucleon-nucleus potentials and that in addition allows a straightforward extension to higher rank according to the desired precision. The separable representation of two-body interactions suggested by Ernst-Shakin-Thaler [7] (EST) looks well suited to achieve this goal. Though early applications of EST were carried out in coordinate space [8], the EST procedure does not depend on a specific representation, and we use it directly in momentum space.

Another crucial ingredient for applying the EST procedure in momentum space to phenomenological nucleon-nucleus optical potentials parameterized via Wood-Saxon functions is the existence of an analytical Fourier transform of those Wood-Saxon functions to momentum space. Strictly speaking this Fourier transform is a series [14]. However, we showed by explicit calculations for a test case n+^{48}Ca [37] in coordinate and momentum space that scattering phase shifts and bound states are within an error of less than 0.1% using only the first term. Thus, we have an 'analytic' representation of Wood-Saxon type phenomenological optical potentials in momentum space, which can be used to obtain transition matrix elements at given energies E_i as input for the EST procedure. At present we derived and implemented a momentum space EST procedure with calculated half-shell transition amplitudes for rank-1 separable transition amplitudes. We are in the process to extend this procedure first to rank-2 and then to arbitrary higher ranks. To validate our momentum space approach we exactly reproduced the r-space calculation of Ref. [8] of the s-wave phase shift for a square well potential with parameters adjusted to fit the deuteron binding energy. As technical detail we want to point out that our implementation of the EST procedure differs from the literature, specifically the Graz group which implemented EST for NN interactions [12, 11].

Plan: Develop self-contained code suites which can be used by the other members of the collaboration. The first set of codes will use as input the parameters of a coordinate space Wood-Saxon optical potential and calculate phase shifts, half-shell transition amplitudes, bound state energies, and bound state wave functions for this potential in momentum space. Those will then serve as input for a second set of codes, which use the input to create a separable representation of the original transition amplitude. This work will be continued through the end of Year 3, with the Ph.D. student L. Hlophe supported half by TORUS and half by DOE contract No. DE-FG02-93ER40756.

3.8.2 Dispersive Optical Potentials

Personnel involved: F.M. Nunes

The dispersive optical model was applied to transfer reactions: a systematic study of (d,p) reactions on closed-shell nuclei using the finite-range adiabatic reaction model was performed

[26] at several beam energies and results were compared to data as well as to predictions using a standard global optical potential. Overall, we found that the dispersive optical model was able to describe the angular distributions as well as or better than the global parameterization. In addition, it also constrained the overlap function. Spectroscopic factors extracted using the dispersive optical model are generally lower than those using standard parameters, exhibit a reduced dependence on beam energy, and are more in line with results obtained from (e,e'p) measurements.

3.8.3 Microscopic Folding Optical Potentials

Personnel involved: Ch. Elster and S. Weppner

The PI Elster and collaborator S.P. Weppner completed work started during the first grant year on developing a microscopic folding optical potential for the reaction ^{6}He(p,p)^{6}He, which takes into account the cluster structure of the ^{6}He nucleus.

In this work we extended the concept of a traditional single-particle folding optical potential in first order in the Watson multiple scattering expansion such that the cluster structure of a halo nucleus is incorporated. In practice, this means that we take into account the internal motion of the valance neutrons with respect to the core. In our work we concentrated on the ^{6}He nucleus, however, the formulation we introduced can be further extended to four or five-body clusters, e.g. to ^{8}He. For our calculations we used the density matrix of the three-body cluster orbital shell model approximation (COSMA) introduced in Refs. [41, 40] for the ^{6}He nucleus. This density matrix is based on single harmonic oscillator wave functions for the s- and p-shell of ^{6}He and allows a straightforward calculation of the required correlation densities needed for the optical potential. The resulting folding optical potential contains a six-dimensional integration over internal vector momenta, which is calculated via Monte Carlo integration.

We calculated the angular distribution of the differential cross section and the analyzing power at 71 MeV, 100 MeV, and 200 MeV/nucleon and compared our results with experimental data at 71 MeV/nucleon [35]. We find that the cluster model lowers the cross section for the small angles and brings it closer to the data. Though we do not describe the very small analyzing power at the small angles, we find that the cluster formulation together with a NN t-matrix which takes into account a modification due to the nuclear medium is able to produce a negative analyzing power at larger angles as suggested by the data.

4 Project Management

Coordination

- The coordinating P.I. supervises the different sub-projects, and ensures the cohesion of the overall project.

- Monthly conference calls ensure that practical information is exchanged, and that research projects, visitors and collaborations are properly coordinated.

- Additional conference calls are set up as needed, and our website (see below) is used to deposit internal documents for discussion.

- Collaborative visits and small-group conference calls and tele-meetings are held on a regular basis to allow for detailed discussions of physics issues.

Website

We have developed a website at http://www.reactiontheory.org that is hosted at MSU. For the public, this site contains general information about our collaboration, our research papers and talks, the workshops and conferences we attend, and lists of relevant experiments.

For ourselves (protected by a password), we have information about our budget, our plans and deliverables, minutes from our meetings and conference calls, and also a place to deposit internal documents for access by the collaboration.

We also use googledocs to share papers and updated reports.

Collaborative visits

June 2010: the whole collaboration met at MSU for planning purposes
August 2010: Elster and Mukhamedzhanov visited MSU for discussions with Nunes and Upadhyay.
October 2010: Mukhamedzhanov visited LLNL to define the resonance problem.
November 2010: We all attended the DNP10 Fall Meeting at Santa Fe, where our monthly meeting was held.
November 2010: Arbanas visited LLNL to discuss methods for semi-direct captures.
December 2010: Thompson visited MSU to discuss breakup calculations.
December 2010: Elster visited LLNL to discuss L-dependence of optical potentials.
February 2011: Mukhamedzhanov visited LLNL to work on transfers to resonances.
February 2011: Thompson visited OU for work on L-dependent optical potentials.
April 2011: Ch. Elster and N. Upadhyay visited TAMU
May 2011: I.J. Thompson, F. Nunes and J. Escher attended the ECT* workshop "Recent Developments in Transfer and Knockout Reactions"
July 2011 : N. Upadhyay visited OU
June 2011: the whole collaboration met at MSU for annual meeting and DOE review
Oct 2011: I.J. Thompson, A. Mukhamedzhanov, C. Elster and F. Nunes had a collaboration meeting during the DNP meeting at MSU
Oct 2011: Ch. Elster visited MSU
Nov 2011: Ch. Elster visited MSU
Dec 2011: I.J. Thompson visited MSU
March 2012: Ch. Elster and L. Hlophe visited MSU
June 2012: Ch. Elster, J. Escher and F. Nunes collaboration meeting at the HITES conference
June 2012: the whole collaboration met at MSU for annual meeting

5   Postdoctoral Staff and Visits

TORUS supported postdoctoral researchers and students

Neelam Upadhyay	PostDoc.	MSU	July 2010 – June 2013
Vasily Eremenko	PostDoc.	Texas A&M	Jan. 2013 – May 2014
Linda Hlophe	Grad.Stud.	Ohio U	March 2012 – Dec 2012

Neelam Upadhyay was hired as the postdoctoral staff in this project. She was hired from a different field (few-body reactions with eta mesons). Neelam arrived at MSU on the 15th July 2010, and spent about 6 months getting famililar with the intricacies of CDCC calculations. Then she carried out CDCC calculations regarding the breakup of deuterons for a number of test cases to compare with exact Faddeev (see Section 3.2), which where then published as regular article [36]. She studied an existing AGS code (visit to Texas in April 2011) and familiarized herself with the concept of separable interactions (visit to Ohio in July 2011). More recently Neelam has been meticulously deriving the general form for the equations to be implemented by our collaboration and is now preparing to numerically handle Coulomb wave functions in momentum space.

Neelam has had the opportunity to participate in schools and has given a number of talks, including invited seminars and contributions at conferences. Finally, she initiated a collaboration with the experimentalist Anissa Bey from Univ. Tennessee regarding the analysis of data obtained at ORNL. This work will be published in the near future.

Vasily Eremenko arrived at Texas A&M after completing his PhD at Moscow State University (Russia) in March 2012. He worked with A. Mukhamedzhanov on the derivation of the generalized Faddeev equations that include target excitations and an explicit inclusion of the Coulomb interaction [23]. Starting January 2013 Vasily will be joining the TORUS grant with the goal of explicit implementation of the formulation laid out in [23].

Linda Hlophe is a 2nd year graduate student at Ohio University. In Spring 2012 he started implementing the Fourier transform of Wood-Saxon type optical potentials into a momentum space scattering code. Then he learned about separable interactions and is currently deriving separable partial wave transition matrix elements for a n-^{48}Ca optical potential. This project is part of his Ph.D. thesis.

External Visitors

- Antonio Fonseca (University of Lisbon): expert in few-body methods and in particular the AGS method. Visited in November 2010.
- Seth Waldeck (Washington University in St Louis): student of Wim Dickhoff and working on the dispersion optical model. Visited in January 2011.
- S.P. Weppner (Eckerd College, FL) spent his sabbatical in the academic year 2010-11 from Eckerd College (FL) at Ohio University, for the work of his stay was provided by Ohio University (Institute of Nuclear and Particle Physics, and Department of Physics and Astronomy) and a small portion by the U.S. Department of Energy under Grant No. DE-FG02-93ER40756.

- D.J. Ernst (Vanderbilt University, TN), author of the EST methods visits Ohio University in the first week of September 2012.

Other Collaborators

These collaborations contributed to our project, but were not funded by this grant:
- Frank Dietrich (LLNL)
- Arthur Kerman (MIT emeritus, now University of Tennessee at Knoxville).
- Raymond Kozub (Tennessee Technological University)
- Kate Jones (University of Tennessee at Knoxville)
- Steve Weppner (Eckerd College, FL)
- Azamat Orazbayev (Ph.D. student at OU)
- Walter Glöckle (Ruhr-Universität Bochum, Germany)
- N.B. Nguyen (Ph.D student at MSU)
- Wim Dickhoff and Seth Waldecker (Washington University, Missouri)
- B.A. Brown (MSU)

Planned Visitors in Year 3

We plan to support the visits of the following people in Year 3 as visitors or consultants:
- Peter C. Tandy (Kent State Univ., OH) to visit OU
- Steve Weppner (Eckerd College, FL) to visit OU
- Rimas Lazauskas to visit MSU
- Arnas Deltuva to visit MSU

6 Plans for Second Half of Project

1. Implementation of the Surface Method for transfers to resonances specified by R-matrix parameters, for both DWBA and CDCC scattering. Determine exterior prior and interior post contributions for such transfers, to predict the accuracy of the Surface Approximation. Make code available for experimental groups.

2. Formulate low-rank separable expansions for optical potentials, with explicit treatment of the Coulomb potential, for calculation in AGS equations.

3. Implementation of Coulomb-distorted AGS equations for d+$A \rightarrow$p + B transfer reactions.

4. Determine the uncertainty of capture rates introduced by currently-used energy-averaging methods and investigate whether a new treatment is required that incorporates doorway resonances.

5. Implement semi-microscopic methods for doorway states in neutron scattering and capture. Use models for pygmy dipole resonances and isobar-analogue resonances, including multistep-transfer contributions, to compute cross sections for selected neutron-rich nuclides.

7 Deliverables

7.1 Publications

1. Published paper [24]: Physical Review C 82, 051601(R) (2010) – Published Nov 3, 2010
   Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors. A. M. Mukhamedzhanov and A. S. Kadyrov

   Future exact many-body theory will allow us to calculate nuclear reactions based on the adopted NN and many-body nuclear potentials. But NN potentials are not observable and there are an infinite number of the phase equivalent NN potentials related via finite-range unitary transformations.We show that asymptotic normalization coefficients, which are the amplitudes of the asymptotic tails of the overlap functions, are invariant under finite range unitary transformations but spectroscopic factors are not. We prove also that the exact amplitudes for the (d,p), (d,pn), and (e,e′p) reactions determining the asymptotic behavior of the exact scattering wave functions in the corresponding channels, in contrast to spectroscopic factors, are invariant under finite-range unitary transformations. Moreover, the exact reaction amplitudes are not parameterized in terms of the spectroscopic factors and nuclear reactions in the exact approach cannot provide a tool to determine spectroscopic factors which are not observable.

2. Published paper [29]: Phys. Rev. C 83, 034610 (2011) – Published March 22, 2011
   Improved description of ^{34,36,46}Ar(p,d) transfer reactions
   F. M. Nunes, A. Deltuva, and June Hong.

   An improved description of single neutron stripping from ^{34,36,46}Ar beams at 33 MeV/nucleon by a hydrogen target is presented and the dependence on the neutron-proton asymmetry of the spectroscopic factors is further investigated. A finite range adiabatic model is used in the analysis and compared to previous zero range and local energy approximations. Full three-body Faddeev calculations are performed to estimate the error in the reaction theory. In addition, errors from the optical potentials are also evaluated. From our new spectroscopic factors extracted from transfer, it is possible to corroborate the neutron-proton asymmetry dependence reported from knockout measurements.

3. Published paper [22]: Phys. Rev. **C 83**, 055805 (2011) – Published May 31, 2011.
   Reexamination of the astrophysical S factor for the $\alpha + d \rightarrow^6 \text{Li} + \gamma$ reaction,
   A. M. Mukhamedzhanov, L. D. Blokhintsev and B. F. Irgaziev.

   Recently to study the radiative capture $\alpha + d \rightarrow {}^6\text{Li} + \gamma$ process a new measurement of the ^{6}Li(A 150 MeV) dissociation in the field of ^{208}Pb has been reported in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)]. However, the dominance of the nuclear breakup over the Coulomb one prevented from obtaining the information about the $\alpha + d \rightarrow {}^6\text{Li} + \gamma$ process from the breakup data. The astrophysical $S_{24}(E)$ factor has been calculated within the $\alpha - d$ two-body potential model with potentials determined from the fits to the $\alpha - d$ elastic scattering phase shifts. However, the scattering phase shift itself doesn't provide a unique $\alpha - d$ bound state potential, which is the most crucial input when calculating the $S_{24}(E)$ astrophysical factor at astrophysical energies. In this work we emphasize an important role of the asymptotic normalization coefficient (ANC) for $^6\text{Li} \rightarrow \alpha + d$, which controls the overall normalization of the peripheral $\alpha + d \rightarrow {}^6\text{Li} + \gamma$ process and is determined by the adopted $\alpha - d$ bound state potential. We demonstrate that the ANC previously determined from the $\alpha - d$ elastic scattering s-wave phase shift in [Blokhintsev *et. al* Phys. Rev. **C 48**, 2390 (1993)] gives $S_{24}(E)$, which is at low energies about 38% lower than the one reported in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)]. We recalculate also the reaction rates, which are also lower than those obtained in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)].

4. Published paper [20]: Physical Review **C 84**, 024616 (2011) – Published August 29 , 2011.
   Asymptotic normalization coefficients from the ^{14}C(d, p)^{15}C reaction,
   A.M. Mukhamedzhanov, V. Burjan, M. Gulino, Z. Hons, V. Kroha, M. McCleskey, J. Mrazek, N. Nguyen, F. M. Nunes, S. Piskor, S. Romano, M.A. L. Sergi, C. Spitaleri, and R. E. Tribble.

   The ^{14}C(n,γ)^{15}C reaction plays an important role in inhomogeneous big bang models. In Timofeyuk et al. [Phys. Rev. Lett. 96 162501

(2006)] it was shown that the ^{14}C(n,γ)^{15}C radiative capture at astrophysically relevant energies is a peripheral reaction, i.e., the overall normalization of its cross section is determined by the asymptotic normalization coefficient (ANC) for ^{14}C $\rightarrow^{14}$C+n. Here we present new measurements of the ^{14}C(d, p)^{15}C differential cross sections at deuteron incident energy of 17.06 MeV and the analysis to determine the ANCs for neutron removal from the ground and first excited states of ^{15}C. The results are compared with previous estimations.

5. Published paper [15]: Phys. Rev. C 84, 034601 (2011) – Published September 1, 2011
Direct reaction measurements with a ^{132}Sn radioactive ion beam
K. L. Jones, F. M. Nunes, *et al.*

The (d,p) neutron transfer and (d,d) elastic scattering reactions were measured in inverse kinematics using a radioactive ion beam of ^{132}Sn at 630 MeV. The elastic scattering data were taken in a region where Rutherford scattering dominated the reaction, and nuclear effects account for less than 8% of the elastic scattering cross section. The magnitude of the nuclear effects, in the angular range studied, was found to be independent of the optical potential used, allowing the transfer data to be normalized in a reliable manner. The neutron-transfer reaction populated a previously unmeasured state at 1363 keV, which is most likely the single-particle $3p_{1/2}$ state expected above the N=82 shell closure. The data were analyzed using finite-range adiabatic-wave calculations and the results compared with the previous analysis using the distorted-wave Born approximation. Angular distributions for the ground and first-excited states are consistent with the previous tentative spin and parity assignments. Spectroscopic factors extracted from the differential cross sections are similar to those found for the one-neutron states beyond the benchmark doubly magic nucleus ^{208}Pb.

6. Published paper [6]: The Astrophysical Journal Letters, **739**, L54 (2011) – Published September 9, 2011.
The fluorine destruction in stars: first experimental study of the ^{19}F$(p, \alpha_0)^{16}$O reaction at astrophysical energies,
M. La Cognata, A. M. Mukhamedzhanov, C. Spitaleri, I. Indelicato, M. Aliotta, V. Burjan, S. Cherubini, A. Coc, M. Gulino, Z. Hons, G. G. Kiss, V. Kroha, L. Lamia, J. Mrazek, S. Palmerini, S. Piskor, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, and A. Tumino.

The ^{19}F$(p, \alpha)^{16}$O reaction is an important fluorine destruction channel in the proton-rich outer layers of asymptotic giant branch (AGB) stars and it might also play a role in hydrogen-deficient post-AGB star nucleosynthesis. So far, available direct measurements do not reach the energy region of astrophysical interest ($E_{cm} \lesssim 300$ keV), because of the hindrance effect of the Coulomb barrier. The Trojan Horse (TH) method was thus used to access this energy region, by extracting the quasi-free contribution to the ^{2}H(^{19}F, α^{16}O)n and the ^{19}F(^{3}He, α^{16})d reactions. The TH measurement of the α_0 channel shows the presence of resonant structures not observed before, which cause an increase of the reaction rate at astrophysical temperatures up to a factor of 1.7, with potential consequences for stellar nucleosynthesis.

7. Publishes paper [34]: Phys. Rev. C 84, 035805 (2011) – Published September 14, 2011
Asymptotic normalization of mirror states and the effect of couplings
L. J. Titus, P. Capel, and F. M. Nunes.

Assuming that the ratio between asymptotic normalization coefficients of mirror states is model independent, charge symmetry can be used to indirectly extract astrophysically relevant proton capture reactions on proton-rich nuclei based on information on stable isotopes. The assumption has been tested for light nuclei within the microscopic cluster model. In this work we explore the Hamiltonian independence of the ratio between asymptotic normalization coefficients of mirror states when deformation and core excitation is introduced in the system. For this purpose we consider a phenomenological rotor+N model where the valence nucleon is subject to a deformed mean field and the core is allowed to excite. We apply the model to ^{8}Li/^{8}B, ^{13}C/^{13}N, ^{17}O/^{17}F, ^{23}Ne/^{23}Al, and ^{27}Mg/^{27}P. Our results show that, for most studied cases, the ratio between asymptotic normalization coefficients of mirror states is independent of the strength and multipolarity of the couplings induced. The exception is for cases in which there is an s-wave coupled to the ground state of the core, the proton system is loosely bound, and the states have large admixture with other configurations. We discuss the implications of our results for novae.

8. Published paper [28]: Phys. Rev. C 84, 034607 (2011) – Published September 19, 2011
Adiabatic approximation versus exact Faddeev method for (d,p) and (p,d) reactions

F. M. Nunes and A. Deltuva.

The finite-range adiabatic wave approximation (ADWA) provides a practical method to analyze (d, p) or (p, d) reactions; however, until now the level of accuracy obtained in the description of the reaction dynamics has not been determined. In this work, we perform a systematic comparison between the finite-range adiabatic wave approximation and the exact Faddeev method. We include studies of ^{11}Be(p, d)^{10}Be(g.s.) at Ep=5, 10, and 35 MeV; ^{12}C(d, p)^{13}C(g.s.) at Ed=7, 12, and 56 MeV; and ^{48}Ca(d, p)^{49}Ca(g.s.) at Ed=19, 56, and 100 MeV. Results show that the two methods agree within $\sim$5 % for a range of beam energies (E_d =20 – 40 MeV) but differences increase significantly for very low energies and for the highest energies. Our tests show that ADWA agrees best with the Faddeev method when the angular momentum transfer is small ?l=0 and when the neutron-nucleus system is loosely bound.

9. Published paper [5]: Physics Letters B **705**, 112 (2011) – Published September 28, 2011
One-neutron halo structure by the ratio method
P. Capel, R. C. Johnson, F. M. Nunes

We present a new observable to study halo nuclei. This new observable is a particular ratio of angular distributions for elastic breakup and scattering. For one-neutron halo nuclei, it is shown to be independent of the reaction mechanism and to provide significant information about the structure of the projectile, including binding energy, partial-wave configuration, and radial wave function of the halo. This observable offers new capabilities for the study of nuclear structure far from stability.

10. Published paper [26]: Phys. Rev. C 84, 044611 (2011) – Published October 14, 2011
Transfer reactions and the dispersive optical model
N. B. Nguyen, S. J. Waldecker, F. M. Nunes, R. J. Charity, and W. H. Dickhoff.

The dispersive optical model is applied to transfer reactions. A systematic study of (d, p) reactions on closed-shell nuclei using the finite-range adiabatic reaction model is performed at several beam energies and results are compared to data as well as to predictions using a standard global optical potential. Overall, we find that the dispersive optical model is able to describe the angular distributions as well as or better than the global parametrization. In addition, it also constrains the overlap function. Spectroscopic factors extracted using the dispersive optical model are generally lower than those using standard parameters, exhibit a reduced dependence on beam energy, and are more in line with results obtained from (e,e'p) measurements.

11. Published paper [21]: Phys. Rev. C 84, 044616 (2011) – Published October 21, 2011.
Theory of deuteron stripping: From surface integrals to a generalized R-matrix approach,
A. M. Mukhamedzhanov.

There are two main reasons for absence of the practical theory of stripping to resonance states which could be used by experimental groups: numerical problem of the convergence of the DWBA matrix element when the full transition operator is included and it is unclear what spectroscopic information can be extracted from the analysis of transfer reactions populating the resonance states. The purpose of this paper is to address both questions. The theory of the deuteron stripping is developed, which is based on the post continuum discretized coupled channels (CDCC) formalism going beyond of the DWBA and surface integral formulation of the reaction theory [A. S. Kadyrov et al., Ann. Phys. **324**, 1516 (2009)]. First, the formalism is developed for the DWBA and then extended to the CDCC formalism, which is ultimate goal of this work. The CDCC wave function takes into account not only the initial elastic $d+A$ channel but also its coupling to the deuteron breakup channel $p+n+A$ missing in the DWBA. Stripping to both bound states and resonances are included. The convergence problem for stripping to resonance states is solved in the post CDCC formalism. The reaction amplitude is parametrized in terms of the reduced width amplitudes (ANCs), inverse level matrix, boundary condition and channel radius, that is the same parameters which are used in the conventional R-matrix method. For stripping to resonance states many-level, one and two-channel cases are considered. The theory provides a consistent tool to analyze both binary resonant reactions and deuteron stripping in terms of the same parameters.

12. Published paper [4]: Phys. Rev. C 85, 044604, (2012) – Published April 2, 2012.
Comparing non-perturbative models of the breakup of neutron-halo nuclei
P. Capel, H. Esbensen and F.M. Nunes.

Breakup reactions of loosely-bound nuclei are often used to extract structure and/or astrophysical information. Here we compare three

non-perturbative reaction theories often used when analyzing breakup experiments, namely the continuum discretized coupled channel model, the time-dependent approach relying on a semiclassical approximation, and the dynamical eikonal approximation. Our test case consists of the breakup of ^{15}C on Pb at 68 MeV/nucleon and 20 MeV/nucleon.

13. Published paper [38]: Phys. Rev. C 85, 054621, (2012) – Published April 23, 2012.
Elastic Scattering of ^{6}He based on a Cluster Description, S. P. Weppner and C. Elster.

Elastic scattering observables (differential cross section and analyzing power) are calculated for the reaction ^{6}He(p,p)^{6}He at projectile energies starting at 71 MeV/nucleon. The optical potential needed to describe the reaction is derived describing ^{6}He in terms of a ^{4}He-core and two neutrons. The Watson first order multiple scattering ansatz is extended to accommodate the internal dynamics of a composite cluster model for the ^{6}He nucleus scattering from a nucleon projectile. The calculations are compared with the recent experiments at the projectile energy of 71 MeV/nucleon. In addition, differential cross sections and analyzing powers are calculated at selected higher energies.

14. Published paper [36]: Phys. Rev. C 85, 054621 (2011) – Published May 25, 2012.
Testing the continuum discretized coupled channel method for deuteron induced reactions
N. J. Upadhyay, A. Deltuva, F. M. Nunes.

The Continuum Discretized Coupled Channels (CDCC) method is a well established theory for direct nuclear reactions which includes breakup to all orders. Alternatively, the 3-body problem can be solved exactly within the Faddeev formalism which explicitly includes breakup and transfer channels to all orders. With the aim to understand how CDCC compares with the exact 3-body Faddeev formulation, we study deuteron induced reactions on: i) ^{10}Be at $E_d = 21.4, 40.9$ and 71 MeV; ii) ^{12}C at $E_d = 12$ and 56 MeV; and iii) ^{48}Ca at $E_d = 56$ MeV. We calculate elastic, transfer and breakup cross sections. Overall, the discrepancies found for elastic scattering are small with the exception of very backward angles. For transfer cross sections at low energy $\sim$10 MeV/u, CDCC is in good agreement with the Faddeev-type results and the discrepancy increases with beam energy. On the contrary, breakup observables obtained with CDCC are in good agreement with Faddeev-type results for all but the lower energies considered here.

15. Published paper [31]: Phys. Rev. Letts. 108, 192701 (2012) – Published May 8, 2012.
Halo nucleus ^{11}Be: a spectroscopic study via neutron transfer
K.T. Schmitt, K.L Jones, A. Bey, S.H. Ahn, D.W. Bardayan, J.C. Blackmon, S. Brown, K.Y. Chae, K.A. Chipps, J.A. Cizewski, K. I. Hahn, J.J. Kolata, R.L. Kozub, J.F. Liang, C. Matei, M. Matos, D. Matyas, B. Moazen, C. Nesaraja, F.M. Nunes, P.D. O'Malley, S.D. Pain, W.A. Peters, S.T. Pittman, A. Roberts, D. Shapira, J.F. Shriner Jr., M.S. Smith, I. Spassova, D.W. Stracener, A.N. Villano and G. Wilson.

Despite ^{11}Be being the best known example of a one-neutron halo nucleus, and one of the most heavily-studied nuclei in recent years, the spectroscopic factors for the two bound states are exceedingly poorly constrained. The (d,p) reaction has been performed in inverse kinematics using a beam of the long-lived isotope ^{10}Be to study both the ground state and the unusual bound excited state halo in ^{11}Be. By performing the reaction at a number of beam energies, studying the elastic channel as well as the transfer channels, and using a theoretical framework that explicitly includes deuteron breakup, consistent spectroscopic factors for these two states have been extracted.

16. Published paper [27]: Proceedings CGS14, World Scientific, in press.
Are present reaction theories for studying rare isotopes good enough?
F. M. Nunes, P. Capel, R.J. Charity, A. Deltuva, W.Dickhoff, H. Esbensen, R.C. Johnson, N.B. Nguyen, N.J. Upadhyay, S.J. Waldecker..

Rare isotopes are most often studied through nuclear reactions. Nuclear reactions can be used to obtain detailed structure information but also in connection to astrophysics to determine specific capture rates. In order to extract the desired information it is crucial to have a reliable framework that describes the reaction process accurately. A few recent developments for transfer and breakup reactions will be presented. These include recent studies on the reliability of existing theories as well as effort to reduce the ambiguities in the predicted observables.

7.2 Preprints and Reports

1. Submitted to monograph chapter [33]: '50 Years of Nuclear BCS', Eds. R.A. Broglia and V. Zelevinsky, World Scientific.
   Reaction mechanisms of pair transfer, I.J. Thompson

   The mechanisms of nuclear transfer reactions are described for the transfer of two nucleons from one nucleus to another. Two-nucleon overlap functions are defined in various coordinate systems, and their transformation coefficients given between coordinate systems. Post and prior couplings are defined for sequential transfer mechanisms, and it is demonstrated that the combination of 'prior-post' couplings avoids non-orthogonality terms, but does not avoid couplings that do not have good zero-range approximations. The simultaneous and sequential mechanisms are demonstrated for the ^{124}Sn(p,t)^{122}Sn reaction at 25 MeV using shell-model overlap functions. The interference between the various simultaneous and sequential amplitudes is shown.

2. Preprint [23]: arXiv: 1206.3791 (2012), submitted to Phys. Rev. C:
   Generalized Faddeev equations in the Alt-Grassberger-Sandhas form for deuteron stripping with explicit inclusion of target excitations and Coulomb interaction,
   A.M. Mukhamedzhanov, V. Eremenko and A.I. Sattarov,

   Theoretical description of reactions in general, and the theory for (d, p) reactions, in particular, needs to advance into the new century. Here deuteron stripping processes off a target nucleus consisting of A nucleons are treated within the framework of the few-body integral equations theory. The generalized Faddeev equations in the AGS form, which take into account the target excitations, with realistic optical potentials provide the most advanced and complete description of the deuteron stripping. The main problem in practical application of such equations is the screening of the Coulomb potential, which works only for light nuclei. In this paper we present a new formulation of the Faddeev equations in the AGS form taking into account the target excitations with explicit inclusion of the Coulomb interaction. By projecting the $(A + 2)$-body operators onto target states, matrix three-body integral equations are derived which allow for the incorporation of the excited states of the target nucleons. Using the explicit equations for the partial Coulomb scattering wave functions in the momentum space we present the AGS equations in the Coulomb distorted wave representation without screening procedure. We also use the explicit expression for the off-shell two-body Coulomb scattering T-matrix which is needed to calculate the effective potentials in the AGS equations. The integrals containing the off-shell Coulomb T-matrix are regularized to make the obtained equations suitable for calculations. For NN and nucleon-target nuclear interactions we assume the separable potentials what significantly simplifies solution of the AGS equations.

3. Submitted to Phys. Rev. Lett.: [17]
   Neutron single particle structure in ^{131}Sn and direct neutron capture cross sections
   R. L. Kozub, G. Arbanas, A. S. Adekola, D. W. Bardayan, J. C. Blackmon, K.Y. Chae, K. A. Chipps, J. A. Cizewski, L. Erikson, R. Hatarik, W. R. Hix, K. L. Jones, W. Krolas, J. F. Liang, Z. Ma, C. Matei, B. H. Moazen, C. D.Nesaraja, S. D. Pain, D. Shapira, J. F. Shriner, Jr., M. S. Smith, and T. P. Swan.

   Recent calculations suggest that the rate of neutron capture by 130Sn has a significant impact on late-time nucleosynthesis in the r-process. Direct capture into low-lying bound states is expected to be significant in neutron capture near the N=82 closed shell, so r-process reaction rates may be strongly impacted by the properties of neutron single particle states in this region. In order to investigate these properties, the (d, p) reaction has been studied in inverse kinematics using a 630 MeV beam of ^{130}Sn (4.8 MeV/u) and a $(CD_2)_n$ target. An array of Si strip detectors, including SIDAR and an early implementation of the ORRUBA, was used to detect reaction products. Results for the ^{130}Sn(d, p)^{131}Sn reaction are found to be very similar to those from the previously reported ^{132}Sn(d, p)^{133}Sn reaction. Direct-semidirect (n, γ) cross section calculations, based for the first time on experimental data, are presented. The uncertainties in these cross sections are thus reduced by orders of magnitude from previous estimates.

4. Submitted to Phys. Rev. C: [39]
   Structures of Exotic $^{131;133}$Sn Isotopes for r-process nucleosythesis

Shi-Sheng Zhang, M. S. Smith, G. Arbanas, and R. L. Kozub.

Background Four strong single-particle bound levels with strikingly similar level spacings have recently been measured in ^{131}Sn and ^{133}Sn. This similarity has not yet been addressed with a theoretical nuclear structure model. Information on these single particle bound levels, as well as on resonant levels above the neutron capture threshold, are also needed to determine neutron capture cross sections – and corresponding capture reaction rates – on $^{130;132}$Sn. The ^{130}Sn(n, γ) rate was shown in a recent sensitivity study to significantly impact the synthesis of heavy elements in the r-process in supernovae. **Purpose** Understand the structure of bound and resonant levels in $^{131;133}$Sn, and determine if the densities of unbound resonant levels are sufficiently high to warrant statistical model treatments of neutron capture on $^{130;132}$Sn. Method Single-particle bound and resonant levels for $^{131;133}$Sn are self-consistently calculated by the analytical continuation of the coupling constant (ACCC) based on a relativistic mean field (RMF) theory with BCS approximation. **Results** We obtain four strong single-particle bound levels in both $^{131;133}$Sn with an ordering that agrees with experiments and spacings that, while differing from experiment, are consistent between the Sn isotopes. We also find at most one single-particle level in the effective energy range for neutron captures in the r-process. **Conclusions** Our RMF+ACCC+BCS model successfully reproduces observed single-particle bound levels in $^{131;133}$Sn and self-consistently predicts single-particle resonant levels with densities too low for widely used traditional statistical model treatments of neutron capture cross sections on $^{130;132}$Sn employing Fermi gas level density formulations.

7.3   Presentations

1. *Improving the theory for transfer reactions*, Invited talk by F.M. Nunes, INPC July 2011, Vancouver, Canada.

2. *Where did matter come from?*, Colloquium by F.M. Nunes, University of Michigan Dearborn, Dearborn, U.S.A.

3. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, University of Notre Dame, South Bend, U.S.A.

4. (d, p) *reactions. Simple or complicated*, Invited talk by A.M. Mukhamedzhanov, 7 April 2010 at the ECT* "Reactions and Nucleon Properties in Rare Isotopes", Trento, Italy, April 6-10, 2010.

5. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 22 September 2010 at ATOMKI, Debrecen, Hungary.

6. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 26 October 2010 at the ECT* "Workshop on Limits of existence of Light Nuclei", Trento, Italy, October 25-30, 2010

7. *Neutron Matter as a Composite Bose-Fermi Superfluid*, Contributed talk by G. Arbanas, 2011 Fall Meeting of the APS Division of Nuclear Physics, East Lansing, MI (October 26-29, 2011).

8. *Neutron Matter as a Composite Bose-Fermi Superfluid*, Contributed talk by G. Arbanas, the inaugural FUSTIPEN workshop: "Bridging the Atlantic with Exotic Isotope Physics", GANIL, Caen, France (January 18-19, 2011).

9. *Simultaneous and Sequential Contributions to Two-nucleon Transfer Reactions*, Invited talk by I.J. Thompson, November 20, 2010 at the RIKEN workshop "Probing Neutron-Proton Pair Correlations – pairing models, cross section measurements and reaction mechanisms", RIKEN Nishina Center, Japan on November 19-20, 2010.

10. *Nuclear Reactions - a Challenge for Few- and Many-Body Theory* Invited talk by Ch. Elster, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.1

11. *A Nucleon-Nucleus Optical Potential for Rare Isotope Beam Facilities* Contributed talk by Stephen Weppner, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.6

12. *Some remarks on reaction theory for Rare Isotopes*, Contribution by F.M. Nunes, 19 January at FUSTIPEN inauguration, Caen, France.

13. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, 24 Feb at Michigan State University, East Lansing, U.S.A.

14. *Cross sections for astrophysics and other applications,* Invited talk by J. E. Escher, LLNL, at the XXXIV Symposium on Nuclear Physics in Cocoyoc, Mexico, January 2011.

15. *Coupled-channels Neutron Reactions on Nuclei*, Invited Seminar by Ian Thompson at the Institute of Nuclear and Particle Physics, Ohio University, Feb 2011.

16. *Reactions with deuterons within the CDCC formalism*, Contributed Talk by Neelam Upadhyay, APS meeting, April 2011.

17. *Nuclear reactions for astrophysics and other applications*, Invited Talk by Jutta Escher, Notre Dame University, March 2011.

18. *Nuclear reactions for astrophysics and other applications*, Invited Talk by Jutta Escher, Argonne National Laboratory, March 2011.

19. *Uncertainties from theory on transfer reactions*, Invited Talk by Filomena Nunes, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 9, 2011

20. *Compound nucleus production by partial fusion in (d,p) reactions*, Invited Talk by Ian Thompson, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 13, 2011

21. *Using transfer and inelastic scattering mechanisms to infer compound reaction cross sections*, Invited Talk by Jutta Escher, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 2011.

22. *Short-range correlations, nuclear reactions and spectroscopic information*, Invited talk by Akram Mukhamedzhanov, ECT* Workshop on Nuclear Many-Body Open Quantum Systems: Continuum and Correlations in Light Nuclei, Trento, Italy, June 6-10, 2011.

23. *Advancing the theory of transfer reactions*, Invited Talk by Filomena Nunes, UNEDF annual meeting, East Lansing, 21st June 2011

24. *The TORUS project*, Invited Talk by Filomena Nunes, FRIB theory workshop, INT, Seattle, 8th August 2011

25. *Theory and Calculation of Two-nucleon Transfer Reactions*, Invited Talk by Ian Thompson, FRIB theory workshop, INT, Seattle, 8th August 2011

26. *Application of Three-Body Methods in Nuclear Reactions: $^6He(p,p)^6He$*, Inv. Talk, Ch. Elster, INT workshop on 'Interfaces between Nuclear Reactions and Structure', August 8 - September 11, 2011, Seattle, WA.

27. *Are present reaction theories for studying rare isotopes good enough?*, Invited Talk by Filomena Nunes, CGS14, Guelph, 2nd September 2011

28. *Testing formalisms for deuteron breakup and transfer reactions*, Contributed Talk by Neelam Upadhyay, DNP meeting, East Lansing, 28th October 2011.

29. *Elastic Scattering of ^{6}He based on a Cluster Description*, Contributed Talk, S.P. Weppner, Ch. Elster, 2011 Fall Meeting of the APS Division of Nuclear Physics, East Lansing, MI, Bulletin of the American Physical Society, Vol. 56, No 12, BAPS.2011.DNP.JE.2

30. *Microscopic Optical Potentials for the Reaction Helium-6 (p,p) Helium-6*, Invited Talk, Ch. Elster, Mini-workshop on 'Polarization Phenomena in Proton Elastic Scattering from Unstable Nuclei', December 21, 2011, RIKEN, Tokyo, Japan.

31. *Microscopic Optical Potentials for the Reaction Helium-6 (p,p) Helium-6*, Ch. Elster, Seminar, December 2011, RIKEN Nishina Center, Japan.

32. *Interior and Exterior Contributions to Transfer Cross Sections*, Ian Thompson, talk at the International Workshop 'Direct Reactions with Exotic Beams', Pisa, March 2012.

33. *Reaction Theory for Exotic Nuclei*, Invited Seminar by Neelam Upadhyay at Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, India, May 2012.

34. *Reaction Theory for Exotic Nuclei*, Invited Seminar by Neelam Upadhyay at Centre for Excellence in Basic Sciences, University of Mumbai, Mumbai, India, May 2012.

35. *Using R-matrix ideas to describe one-nucleon transfers to resonance states*, Jutta Escher, HITES 2012 conference, New Orleans, June 2012.

36. *Nuclear Reactions: A Challenge for Few- and Many-Body Theory*, Charlotte Elster, HITES 2012 conference, New Orleans, June 2012.

37. *Status of Reaction Theory for Studying Rare Isotopes*, Filomena Nunes, HITES 2012 conference, New Orleans, June 2012.

38. *Status of Reaction Theory for Studying Rare Isotopes*, Filomena Nunes, 13th International Conference on Nuclear Reaction Mechanisms, Varenna, June 2012.

7.4 In Preparation

1. *Theory of the Trojan Horse method*, A. M. Mukhamedzhanov, to be submitted to Phys. Rev. C.

2. *Analysis of the Trojan Horse reactions, A. M. Mukhamedzhanov*, M. La Cognata, R. G. Pizzone, C. Spitaleri, to be submitted to Phys. Rev. C.

3. *New insight into deuteron stripping reactions*, A. M. Mukhamedzhanov, I. J. Thompson and J. Escher, to be submitted to Phys. Rev. Lett.

4. *Coulomb renormalization of the ANC*, A. M. Mukhamedzhanov, to be submitted to Phys. Rev. C.

5. *Exactly solvable pairing Hamiltonian with state-dependent separable pairings*, G. Arbanas, M. E. Pigni and A.K. Kerman, to be submitted to Phys. Rev. C.

6. *Exploring R-matrix ideas for the description of one-nucleon transfers to resonance states*, J.E. Escher, A.K. Mukhamedzhanov, and I.J. Thompson, to be submitted to Proceedings of "Horizons on Innovative Theories, Experiments, and Supercomputing in Nuclear Physics," New Orleans, LA, June 4-7, 2012.

7.5   TORUS Workshops

7.5.1   Mini-workshop on Separabilization of Interactions

Personnel involved: F. Nunes, Ch. Elster

On November 10 and 11, 2011 a Mini-workshop on the Separabilization of two-body interactions was held at MSU with Prof. Ron Johnson (Surrey), George Rawitscher (U. Connecticut), and Scott Bogner (MSU) as invited guests. In addition postdoctoral researcher N. Upadhyay and graduate students N.B. Nguyen and L. Titus participated in the workshop. During this short workshop the pros and cons of various approaches to representing nucleon-nucleon and nucleon-nucleus interactions by functional approximations, either Sturmian or separable, were discussed.

7.5.2   Proposed TORUS/INT Workshop

Personnel involved: J.E. Escher

A detailed plan was developed for holding a one-week workshop at the Institute for Nuclear Theory at the University of Washington in Seattle. The focus of the proposed workshop was on deuteron-induced one-nucleon transfer reactions as a means to study the structure of and reaction with exotic nuclei. The proposal was submitted in the summer of 2011 for consideration by the INT advisory committee. It was ranked third among all proposals and tentatively scheduled for December 2012. Very recently, we were informed that the workshop can only be logistically, but not financially, supported by the INT, due to budget cuts to the Institute.

Plan: Due to reduced TORUS funding and some re-allocation of funds between the TORUS institutions, we decided to not pursue this workshop in Year 3, but to resubmit in Year 4.

8   Acknowledgments

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